

PLANET DETECTION VIA MICROLENSING

Appendix C of the Final Report of the
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1 Overview

Microlensing occurs when a foreground compact object (like a star) moves between an observer and a luminous background object (like another star). The gravitational field of the foreground lens alters the path of the light from the background source, bending it more severely the closer the ray passes to the lens. From the perspective of the observer, the result is the formation of two distorted images of the background source, one on either side of the lens. For lens masses comparable to stellar masses, the separation of these images is too small to be resolved. Microlensing is observable because the increased brightness of the combined images changes with time in a predictable manner.

Microlensing was predicted by Einstein in 1936 [1], and proposed as a method to detect dark matter in the Milky Way by Paczyński in 1986 [2]. Paczyński pointed out that the

relative motion of the source and lens would result in a characteristic brightening and then dimming of the background source; the form of this light curve could be used to separate variability due to lensing from intrinsic stellar variability. Since the alignment required for a detectable lensing signal is quite precise, the chances of any given star being lensed at any time is quite small, $\sim 1 \times 10^{-6}$ in the Galaxy. Nevertheless, a few years after Paczyński’s suggestion, the first microlensing events were detected [3,4,5], and the field has since matured rapidly into a full discipline of astronomy, with implications for studies of dark matter, Galactic structure and — most recently — the search for extra-solar planets, first suggested in 1991 [6].

A planet orbiting a star acting as a microlens will create a distortion in its magnification pattern. If the planet is located in the so-called “lensing zone” of its parent star, perturbed regions of high magnification (including caustics with formally infinite magnification) will be generated. A background source passing (in projection) behind these regions will exhibit a short-lived deviation or anomaly in its microlensing light curve. The power of microlensing as a technique for planet detection is that information about the planet’s mass and orbital radius can be obtained from the light curve of the background source without direct detection of light from the planet *or* its parent star. The phenomenon of “resonant lensing” — enhancement of the planetary lensing signal due to the proximity of its more massive parent star — increases the detectability of small planets, making microlensing one of the only viable ground-based methods for earth-mass planet detection, though the technical challenges will be considerable.

Microlensing is also the most promising powerful method to study the statistical frequency of extra-solar planets orbiting typical (random) stars in the Milky Way, even those several kiloparsecs from Earth. The lensing zone corresponds to orbital separations of a few times the Earth-Sun distance (AU) — a good match to many planets in our own Solar System — and the probability of detection is a rather weak function of planetary mass. The mass and orbital separation distributions of detected planets could be determined to within about a factor of three. Microlensing is thus a perfect complement to radial velocity and astrometric techniques that allow the detailed study of nearby planets with larger masses and smaller orbital separations. Recent reviews of the status and prospects of microlensing planetary research are available [7,8,9].

2 Scientific Introduction

In this section, basic microlensing theory is outlined by considering the point-source lens approximation, and then examining how this is altered by the presence of a multiple lens (e.g., planetary system). Since source resolution is an important factor in the detection sensitivity to small mass planets, finite size effects are discussed before proceeding to an estimate of detection sensitivities. In §3, the current and possible future status of real-time microlensing alerts and microlensing monitoring strategies are reviewed, ending with some specific strategies for the detection of jovian and terrestrial mass planets. Recommendations for possible use of ESO-specific resources in the intermediate and long-term are made in §4.

Figure 1: Microlensing light curve and idealized planetary anomaly.

2.1 Point Source-Point Lens

The shape of a microlensing light curve of a point source lensed by a point-lens is described by two parameters, the impact parameter u_{min} and the Einstein crossing time t_E . The time and brightness scales are set by the unamplified source brightness and time of peak magnification, t_o . For a point lens of mass M at a distance D_L from the observer lensing a background source at distance D_S , the magnification A is given by the well-known [2]:

$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}} \quad (1)$$

where u is the angular separation θ_S of source and lens, normalized by the angular Einstein ring radius θ_E . Thus

$$u = \frac{\theta_S}{\theta_E} \quad \text{where} \quad (2)$$

$$\theta_E = \sqrt{\frac{4GM}{c^2 D}} \quad \text{and} \quad D = \frac{D_L D_S}{D_S - D_L}. \quad (3)$$

The physical size of the Einstein ring is given by $R_E = D_L \theta_E$. If the source is moving relative to the observer-lens line-of-sight with a (projected) velocity v_\perp , then the angular source-lens separation u will be a function of time given by

$$u(t) = \sqrt{\frac{(t - t_o)^2}{t_E^2} + u_{min}^2} \quad (4)$$

Figure 2: *Left:* Excess magnification due to planets with mass ratio $q = 10^{-3}$ (left column) and 10^{-4} (right column) for a variety of projected separations near the Einstein ring of the lensing parent star. Bright areas indicate positive excess; dark negative excess. *Right:* The light curve anomalies resulting from source motion along the tracks indicated at left for jovian planets (ie., $q = 10^{-3}$). Time is in units of the Einstein time t_E of the primary event. (From Wambsganss 1997 [10].)

where u_{min} and A_{max} are the normalized impact parameter and magnification at t_o , and t_E is the Einstein ring crossing time $t_E = R_E/v_{\perp}$. Substitution of Eq. (4) into Eq. (1) will result in the familiar microlensing light curve (Fig. 1). For $u = 1$, the source lies at an angular separation $\theta_S = \theta_E$ from the lens, and the total magnification is $A = 1.34$. Typical durations $\hat{t} = 2t_E$ for microlensing events detected in the direction of the Galactic Bulge are on the order of 40 days.

2.2 Binary Lenses (Planets) and Point Sources

Microlensing monitoring is able to detect planets around lenses because multi-lens structure creates complicated perturbations in the magnification patterns on the sky that represent potential positions of the background source that will lead to anomalies from the simple point-source/point lens light curve (Fig. 2). For source positions lying on caustics, the magnification is formally infinite for a point source. A given multiple lens has a fixed magnification pattern relative to the lens; the observed light curve depends on the path that the source takes through this pattern. High-precision, frequent monitoring of known (electronically-alerted) microlensing events can reveal the presence of planets by detecting — and characterizing — these anomalies and comparing them to expectations from planetary system lens models.

In general, the planet-to-parent-star mass ratio, $q = m/M$, and the normalized, projected planet orbital radius $x = a_p/R_E$, can be determined from the light curve itself. Broadly speaking, the planetary mass ratio $q = m/M$ is given by the ratio of the squares of the Einstein rings, and thus observationally by the ratio of the square of the planetary duration to the square of the total event duration. The normalized planet-lens separation can be estimated by recognizing that the lensing range of the planet is so small its projected position must nearly coincide with one of the two images of the primary in order to produce a detectable signal. These image positions can be deduced at the time of the perturbation from the magnifications due to the primary lens and secondary planet at the time of the anomaly. In practice, the morphology of planetary light curve anomalies is quite complex (Fig. 2), and detailed modeling of the excess magnification pattern (the anomalous change in the pattern due to the planet) must be done in order to obtain accurate estimates for q and x . Since the magnification pattern at the location of the two primary images is qualitatively different, detailed, dense monitoring can generally resolve the ambiguity in the planetary position relative to the lens. Reasonable assumptions about the kinematics, distribution, and masses of the primary stellar lenses, together with measurements of the primary event duration $2t_E$ and fraction of blended light from the lens should allow R_E and M to be determined to within a factor $\sim 3 - 5$. Detailed measurements of the planetary light curve anomaly could then yield a_p and m to about the same precision. If other lensing anomalies (eg., source resolution, parallax, caustic crossings) are detected, the precision can be increased.

Theoretically, the probability of planet detection depends on the cross section presented by the magnification pattern (at a given detection threshold) to the path of the source, and on the precision and frequency with which the light curve can be measured. The area of the perturbed region and the duration of the light curve anomaly depend on x and q . Although earth-mass planets are capable of creating a large anomaly in the light curve, the probability that the source will chance to cross the caustic structure is small, since the area enclosed by the caustic structure is larger for larger mass ratios q . Significant magnification is centered on planetary positions x between 0.6 and 1.6: this is known as the “lensing zone.” Since it is normalized by the Einstein ring radius of the primary lens, the lensing zone is a function of the primary mass, M , and the relative lens-source geometry along the line-of-sight; examples are given in Table I.

Table I. Typical Lensing Zones for Galactic Lenses		
Lens Type	disk lens (4 kpc)	bulge lens (6 kpc)
1.0 M_\odot disk star	2.4 - 6.4 AU	2.1 - 5.5 AU
0.3 M_\odot bulge dwarf	1.3 - 3.5 AU	1.1 - 3.0 AU

The region of increased magnification due to a planet orbiting a lensing star is a long, roughly linear region of width approximately equal to Einstein ring of the planet, θ_p , and length along the planet-lens axis about ten times larger [11]. The planetary Einstein ring is related to the Einstein ring of the primary lens via $\theta_p = \sqrt{q}\theta_E$. For small sources, therefore, both the time scale of the duration and the cross section presented to the source

vary linearly with θ_p/θ_E and thus with \sqrt{q} . At the most favorable projected lens-planet separation of $x = 1.3$, and the most ideal lens location (halfway to the Galactic Center), well-sampled observations able to detect 5% perturbations in the light curve would have planet sensitivities given roughly by [11]:

$$\text{ideal detection sensitivity} \approx 1\% (m/M_\oplus)^{1/2} (M/M_\odot)^{-1/2} \quad (5)$$

This ideal sensitivity is relevant only for planets at $x = 1.3$; at the edges of the lensing zone the probabilities are about halved. Detection with this sensitivity requires photometry at the 1% level well-sampled over the duration of the planetary event. Assuming a typical $t_E = 20$ days, the duration of the planetary anomaly is given roughly by the time to cross the planetary Einstein diameter, $2\theta_p$,

$$\text{planetary anomaly duration} = 2\theta_p \approx 1.7 \text{ hours } (m/M_\oplus)^{1/2} (M/M_\odot)^{-1/2}, \quad (6)$$

A true calculation of probabilities must integrate over the projected orbital separations x and the distribution of lenses along the line of sight, and account for uneven sampling.

Before discussing detection probabilities in more detail, finite source effects, which are particularly important for understanding microlensing sensitivities to the detection of small (terrestrial) mass planets, are reviewed.

2.3 Finite Source Effects

The situation changes for sources whose angular size is comparable or larger than the Einstein ring of the secondary: different parts of the source now simultaneously cross different regions of the magnification pattern, and an integration over source area must be done to derive the total magnification. If the angular source size θ_* is large enough to be resolved by the planetary Einstein ring ($\theta_* \gtrsim \theta_p$), the size of the source will influence the size and duration of the planetary perturbation, and thus detection probabilities as well. In this limit, the planetary event lasts longer because the appropriate time scale is the time to cross the source θ_* (not θ_p). Furthermore, the cross section for magnification at a given threshold now scales with θ_*/θ_E (not θ_p/θ_E), and is thus independent of planetary mass. On the other hand, the fractional magnification along a given trajectory is smaller because only a fraction of the source star crosses the highest magnification contour at any given time. The *fractional* planetary magnification is equal to

$$\delta A = \frac{2\theta_p^2}{\theta_*^2 A_o} \quad , \quad (7)$$

where A_o is the magnification due to the primary lens alone (Fig. 1) at the time of the planetary anomaly [12].

Typical giant sources in the bulge, clump giants with a radii about 13 times that of the Sun ($13 R_\odot$), have angular diameters of 7.6 microarcseconds (μas) at 8 kpc. Since a Jupiter-mass planet with $m = 10^{-3} M_\odot$ has an angular Einstein ring radius of 32 μas at 4 kpc and 19 μas at 6 kpc, finite sources effects are small for jupiters when seen against large bulge sources. An Earth-mass planet with $m = 3 \times 10^{-6} M_\odot$, on the other hand, has an angular Einstein ring radius of 1.7 μas at 4 kpc and 1 μas at 6 kpc, and will thus suffer

Figure 3: *Left:* Approximate fractional light curve anomalies for source trajectories and planet masses chosen to give about the deviation. Curves in each subpanel suffer from different amounts of source resolution; smoother curves indicate more resolution. *Right:* Fractional $V - H$ color change for the same planetary light curve anomalies. The degeneracy between small and large planets is broken by the strong color shift apparent during strong source resolution by small planets. (From Gaudi & Gould 1996 [13].)

slight finite source effects even against turn-off stars ($1.7 \mu\text{as}$), though the effect will be greatly reduced compared to giant sources.

It is also important to note that because finite sources effects modify the light curve for a given lensing geometry, an ambiguity is introduced that can lead to a misidentification of the mass ratio q and projected (normalized) orbital radius, x [13]. To first order, a given perturbation can be caused either by a small planet (small q) at small radius (small x) that resolves and thus only partially amplifies the source, or by a much larger planet (large q) at much larger radius (large x) that does not resolve the source. The detection of small mass planets will always remain ambiguous unless this degeneracy is broken through (1) very dense sampling to detect higher order effects in the perturbed light curve shape or (2) the measurement of color terms indicative of source resolution by small mass planets transiting the image of a limb-darkened source (Fig. 3).

2.4 Detection Sensitivities: When has a Planet been Detected?

Detection sensitivities depend on the probability for the source to cross the planetary perturbation zone and the fractional deviation in the brightness of the source during the crossing. In general, crossing probabilities will be larger for larger sources, but the

maximum fractional magnification will be considerably smaller as finite source effects become important.

In Tables II and III below, relevant fiducial values are given for the detection of Jupiter-mass and Earth-mass planets orbiting Solar-mass stars in the disk and or $0.3 M_{\odot}$ bulge dwarfs; both bulge giants ($13 R_{\odot}$) and turn-off stars ($3 R_{\odot}$) are considered separately as sources. Since a sizable fraction of lenses toward the Galactic Bulge are likely to be bulge stars with $M < 1M_{\odot}$ located ~ 6 kpc from us, the bulge dwarf option should be considered as a serious alternative to the oft-quoted $1M_{\odot}$ mass lens in the disk at 4 kpc.

Table II. Sensitivities to Jupiter-Mass Planets				
Lens Type	Giant Sources ($13 R_{\odot}$)		Turn-off Sources ($3 R_{\odot}$)	
	Ideal Sensitivity	Duration	Ideal Sensitivity	Duration
1.0 M_{\odot} disk star	18%	30 hr	18%	30 hr
0.3 M_{\odot} bulge dwarf	32%	55 hr	32%	55 hr

The numbers quoted in Table II are ideal sensitivities relevant only for planets at $x = 1.3$, assuming 1% photometry over the entire light curve to $1.5t_E$ past peak; at the edges of the lensing zone the probabilities are about halved [11]. Integrated over the lensing zone, then, the sensitivities would probably drop to about 75% of the values listed above.

Detailed calculations have been done by Bennett and Rhie [14] for some special cases of low-mass planet detection against clump giants ($R_* = 13R_{\odot}$, $\theta_* = 7.6\mu\text{as}$) and turn-off stars ($R_* = 3R_{\odot}$, $\theta_* = 1.7\mu\text{as}$) in the bulge. Interpolations from their work are used for the estimates of detection sensitivities given in Table III. Their model assumed the so-called “factor-of-two” planetary system model that assumes one planet for every factor of two increase in orbital radius. This model (which is appropriate for our own Solar System) gives detection probabilities that are somewhat higher than single-planet models. Bennett and Rhie [14] also show that if monitoring is stopped at the Einstein Ring ($A=1.34$) rather than at the approximate end of the lensing zone at $1.5 R_E$ ($A=1.13$), detection efficiencies are reduced by only 5-10% for their factor-of-two model.

Table III. Sensitivities to Earth-Mass Planets						
Lens Type	Giant Sources ($13 R_{\odot}$)			Turn-off Sources ($3 R_{\odot}$)		
	δA_{max}	P(D)	Dur	δA_{max}	P(D)	Dur
1.0 M_{\odot} disk star	0.08	0.1%	7.5 hr	> 1	1.6%	1.7 hr
0.3 M_{\odot} bulge dwarf	0.03	$\sim 0\%$	23 hr	0.65	2.6%	5.3 hr

Here, δA_{max} = Maximum Fractional Amplification from Planet

P(D) = Detection Probability at 4% threshold, using 0.5—1% photometry
well-sampled on timescales $t_E/200$ until $1.5t_E$ past peak

Dur = Order of magnitude estimate of Duration = $\hat{t} \equiv 2t_p$

The sensitivities to planet detection given in Tables II and III must assume a definition for “detection.” In principle, such a definition could entail: (a) detecting a deviant point at a certain level of significance, (b) detecting a coherent, significant deviant anomaly (over several points) consistent with a planetary signature, or (c) characterizing the signal as planetary by extracting mass and radii parameters from a fit. In practice, Gould and Loeb [11] (on which Table II is based) assume that a planet is detected if its light curve anomaly somewhere exceeds a 5% threshold. The detailed calculations of Bennett and Rhie [14] provide the basis of the detection probabilities quoted in Table III for small mass planets against giant and turn-off microlensed sources, and include the effects of source resolution. They assume that an anomaly is detected if it exceeds a certain threshold (here taken to be 4%) for a time at least equal to $1/400$ of the event’s total duration, a time about equal to 2.4 hours on average.

Since the optical depth to microlensing is so low ($\sim 1 \times 10^{-6}$), a given planetary anomaly will not repeat, and observations can be made only once for a given planetary system. For this reason, it is likely that in order to convince the scientific public that a planet has been detected, *characterization* of the anomaly, not just its detection, will be required. *In other words, a more robust definition of detection is that the nature of the deviation must be sufficiently well-characterized to allow the mass ratio q and the normalized projected separation x to be determined, thus demonstrating the “planetary” nature of the anomaly.* This more stringent definition has consequences for possible observing strategies for large and small mass planets which are discussed in the following section.

3 Possible Observing Strategies

In order to make a sensible observing strategy for detecting planets via microlensing, one must first decide whether the aim is the detection of large or small mass planets. Since the probabilities for detection decrease with decreasing planetary mass, more microlensing events must be monitored for a small-mass program. Furthermore, the durations of the planetary anomalies are expected to be shorter for smaller mass planets, so the sampling must be more dense in time. Finally, finite source effects are important for the detection of very low mass planets [14], requiring higher photometric accuracy and a strategy for resolving the degeneracy in the planetary parameters that makes it more difficult to determine the mass of the planet if the source is resolved [13]. Taking these considerations into account, one can then formulate separate strategies for the detection via microlensing of large and small mass planets. Peale [8] has suggested, based on one detection scheme [14], that round-the-clock monitoring is more important for terrestrial-mass searches than jovian-mass searches. As we shall see, replacing this definition of detection with one based on not only detecting but *characterizing* the anomaly reverses this conclusion. Longer 1-2 day jovian anomalies require round-the clock monitoring for correct characterization; 2-5 hour terrestrial anomalies against turn-off sources can be characterized from a single site, though total efficiencies are statistically reduced by a factor $1/3$.

Figure 4: *Left:* Logarithmic histogram of time between successive photometric measurements at SAAO and ESO for the 1995 PLANET microlensing monitoring program. *Right:* Formal photometric error as a function of I-band magnitude for a typical PLANET field at Lasilla. Typical $V - I$ color is 1.5 for these fields. The number of stars and median error is given for each measured bin for isolated stars (above) and all detected stars (below). (From Albrow et al. 1997 [16].)

3.1 Photometric Precision: How Precise?

The probabilities of detection estimated in the previous section were based on assumptions about the sampling and photometric accuracy. If one wishes to have sensitivities for “detection” as high as those given in Tables II and III, it is necessary either to perform photometry at the $\ll 1\%$ level in order to detect a single anomalous point at very high signal-to-noise (S/N), or at the 1% level with a sampling rate that includes several points over the planetary anomaly. The latter is strongly recommended if the detection is also to include a characterization of the planetary parameters.

PLANET (Probing Lensing Anomalies NETwork) is a worldwide collaboration of astronomers using semi-dedicated ESO, South African, and Australian telescopes to perform continuous, rapid and precise multi-band CCD photometric monitoring of on-going Galactic microlensing events with photometry that is optimized for the detection of Jovian-mass planets orbiting several AU from Galactic lenses [15]. The events in progress are provided via electronic alerts from microlensing survey teams. PLANET has performed relative photometry to $I \approx 19.5$ ($V \approx 21$) with 1%, 2% and 6-7% precision at $I=15$, $I=17$ and $I=19$ ($V=16.5$, 18.5 , 20.5) respectively (Fig. 4), using the 1m-class telescopes in their network [16]. Despite the fact that their telescopes have smaller aperture, PLANET photometry is ~ 5 times more precise than that of the MACHO team, indicating that image quality, rather than photon statistics, is the ultimate limiting factor for precise photometric monitoring in these very crowded fields.

In sum, in order to obtain reasonable sensitivity to the detection of extra-solar planets, 1% photometry is required on a large enough sample of microlensing alerts. Since crowding limits the photometric precision in these fields, considerations such as image quality, good seeing, and small pixel size dominate over aperture size in determining the systematic errors that set the lower limit on the photometric error.

3.2 Sampling Rate: How Often?

In order to determine the mass ratio q and the normalized projected separation x , the structure of the anomaly must be appropriately characterized over its duration. The duration of the anomaly can be quite varied [10], though sharp peaks are very short-lived. Since the morphology of light curves is quite rich (Fig. 2), about 10 measurements over the perturbation are probably required to characterize the planetary system parameters. Given the duration estimates for planetary anomalies listed in Tables II and III, this suggests sampling rates of about once per 4 hours for jupiters. For earths, adequate coverage would require sampling once per hour or so against giant sources and once per 20 minutes against turn-off sources. Recall that the Bennett and Rhie [14] detection calculations assumed sampling every $t_E/200 \approx 2.4$ hours. Characterization of low-mass planetary systems will thus require much more rapid sampling than detection alone. If the excess magnification is consistent with source resolution ($\delta A < 1$), then very high accuracy and dense photometry and/or multi-band measurements (Fig. 3) must be used to break the degeneracy that can confuse the detection with planets of smaller mass [13].

Not only the sampling rate, but also the continuity of sampling is important to the characterization of the planetary anomaly. A single site will be able to fully monitor individual Earth-mass anomalies, but will miss $\sim 67\%$ of the total number due to insufficient longitude coverage. With perfect weather, a single site would be likely to have a few points on any detectable Jupiter-mass anomaly, but would be unable to pinpoint the position of the anomalous peak or the excess magnification at that peak. Since the duration of a Jupiter-mass anomaly is on the order of a day or two, full coverage via a network of longitudinally-distributed telescopes is indicated. Such a network can also act as a hedge against bad weather. A network of telescopes would also be useful for the detection of Earth-mass planets, but primarily to increase the total number of detections rather than to improve their individual characterization.

3.3 Alerts: How Many?

In order to perform precise, rapid monitoring, it is probably wisest to separate the monitoring effort from the microlensing detection, or survey, effort. With the advent of real-time electronic alerts of on-going microlensing events by the survey teams, this separation of labor is now possible. The PLANET [15,16] and GMAN [17] collaborations now perform such monitoring, keying on the electronic alerts from the survey teams.

The development of a realistic observing strategy must consider whether real-time microlensing alerts will be available in sufficient quality and quantity. In the early part of the bulge season, the number of alerts tends to be smaller because baselines are yet to

be established and the bulge is visible for only a few hours. Table IV lists hours of bulge visibility and numbers of MACHO alerts per month for 1995 and 1996.

A highly speculative estimate of future alert rates is given below. It should also be noted that since the discovery teams monitor many of the same fields, some of the alerts will overlap, so that it is inappropriate to form a simple sum of alerts by individual teams to arrive at the number of total alerts.

Table IV. Current MACHO-team Alert Profile for the Bulge				
Month	1995 Alerts	1996 Alerts	Total	Hrs Visible/ESO night
March	0	4	4	1
April	0	1	1	4
May	14	7	21	6.5
June	4	7	11	9
July	10	3	13	9
August	5	5	10	6.5
September	4	2	6	4
October	1	2	3	1
Totals	38	31	69	

(Note: The MACHO on-line alert software was down in July of 1996 which accounts for the low number of alerts during that time. At the time of this report, 16 events have been alerted by the MACHO team in March and April of 1997.)

Future MACHO alerts: In 1995, the MACHO team issued about 40 bulge alerts, and in 1996, about 30 more. Through 1996, MACHO alerted on only $\sim 25\%$ of its bulge fields [Bennett 1996, private communication], and so in principle could provide more alerts in the future. On the other hand, since its current alerting area has low extinction and therefore more observable stars, it is unlikely that the total number would increase by more than about a factor of two. About 30% of the MACHO alerts are on giants stars as source stars.

Future OGLE alerts: Both EROS II and OGLE II expect to issue some alerts in 1997, although the numbers are uncertain. OGLE has issued alerts in the past (a handful in 1995) and their software has been demonstrated to work in real-time, but they have not yet obtained the baselines ready to issue alerts in the beginning of 1997 [Paczynski 1996, private communication]. When they install their large CCD array, they will have twice the number of pixels as MACHO. However since they will also be performing non-microlensing programs and their first detector will cover only $1/8$ the area, the initial number of OGLE II alerts will be small.

Future EROS alerts: Estimates for the number of 1997 EROS II alerts are quite uncertain, but it is expected that the total number of EROS II alerts will be comparable to that of MACHO [Rich 1996, private communication]. The new EROS II detector has twice the area of MACHO. Their software alert trigger has been written, but is not yet demonstrably working on real data. If the EROS II bulge strategy remains to survey an area in the bulge at approximately 8 times that of the current MACHO alert area in

order to focus on giant stars as source stars, then the number of EROS II *giant* alerts should exceed the current MACHO by a factor of 4-8, yielding 50-100 giant alerts per season when in full operation. Since most of the new fields will be much more heavily extincted and the exposures will be shorter, the fraction of EROS II turn-off alerts would be expected to be smaller than the MACHO turn-off alert fraction. Sufficient baseline data has been obtained for only a fraction of the total number of EROS II fields, so the initial number of 1997 EROS II alerts is likely to be small even if the trigger is operational at the beginning of the bulge season. As the baselines are acquired (1-2 months required), the number of alerts might be expected to increase rapidly over the 1997 season, and hold steady in 1998.

In summary, 1997 is likely to be a transition year, with EROS II beginning to alert (with emphasis on giant sources) and OGLE II coming back on-line with alert capability over an even larger area in 1998. It is therefore reasonable to expect that MACHO will provide at least 30-40 alerts in 1997, with an uncertain number of additional alerts provided by OGLE and EROS II. Some of the alerts from different discovery teams will “overlap.” By the end of the 1997 season or beginning of the 1998 season, it is conceivable that 50 - 100 independent giant alerts may be issued by all microlensing survey teams; the total number will depend crucially on EROS II capability to detect and alert lensing of giants in dustier fields. On the other hand, because of their (expected) shorter exposure times, EROS II will probably provide fewer turn-off alerts than the full OGLE II experiment. When OGLE II becomes operational with its larger detector, and depending on whether MACHO begins to alert more fields, perhaps 75 - 150 alerts on turn-off stars may be expected as soon as 1998.

3.4 Jovian ($m = 10^{-3}$ to $10^{-4} M_{\odot}$ mass) Planets

Due to crowding and extinction, accurate photometry in the bulge is most easily done on bright, red objects. Planets with $10^{-4} < m < 10^{-3} M_{\odot}$ are large enough that finite source effects are not a difficulty, so that the best photometry can be obtained with a monitoring strategy based on lensed subgiants and giants. In addition, one gains the following benefits: (1) nearly all sources lie in a small range of distance, removing selection effects due to source position, (2) blending by foreground stars is less important for brighter sources, (3) shorter exposures can be taken allowing more objects to be monitored, and/or more frequent monitoring if an anomaly is detected, (4) source star spectroscopy is easier to obtain in order to type the source and thus obtain its physical size and distance.

These are strong reasons to focus on a strategy based on giants ($V \lesssim 17.5$) for detection of jovian planets: accurate photometry with sufficient sampling is made much easier, enhancing both the chances for detection and the accuracy of the deduced planetary parameters. The concern is whether giant alerts will be present in sufficient numbers. In the past the number of lensed giants have been reported in rather small numbers, reflecting their small fractional numbers in the bulge. As explained in the previous section, however, when the EROS II alert trigger is working and baselines have been taken, it is reasonable to expect that at least 50 giant alerts will be given per season. If the more heavily extincted EROS II fields are as giant-dense as the current MACHO alert fields, the number of giant alerts could be as high as 100 per season.

Since about 25-30% of these giant-source events will be on-going at any given time, it may then be necessary to follow 12 – 30 giant events simultaneously. In order to be sensitive to planets with masses of $10^{-4}M_{\odot}$, sampling every 1.5 hours or so will be required to achieve 10 points over the deviation. In the most extreme case, this allows no more than about 3 minutes per event for exposure plus overhead. The experience of PLANET has shown that 2 – 4 minute exposures on a 1m telescope are sufficient to achieve 1-2% relative I-band photometry for clump giants in these crowded fields [16]. Taking 3 min as typical with an additional 1.3 minute for overhead yields 21 giant sources monitored at 1.5 hour sampling per night with a 1m telescope, or about 70 – 80 giants per bulge season. Thus, for the detection of planets in this mass range, larger apertures are required for I-band monitoring only if the number of giant events per night exceeds ~ 20 , or the number per season exceeds ~ 75 .

Note that planets in the mass range $m = 10^{-3}$ to $10^{-4}M_{\odot}$ have durations of 10 – 55 hours and thus benefit strongly from continuous 24-hour coverage. Furthermore, simultaneous observations in an infrared band would enable shorter exposures for the same signal-to-noise, while providing a mechanism to break the small planet-large planet degeneracy for planets that resolve the giant sources. These considerations have led the PLANET collaboration to already begin pursuing a search strategy for large- to moderate-sized planets using 1m telescopes scattered about the southern hemisphere, some of which will be equipped with cameras capable of simultaneous imaging in the optical and IR.

In sum, since 50-100 giant alerts may be expected beginning in 1998 from all survey teams, the sensitivities presented in Table II suggest that if all lenses have a planet of mass $m > 10^{-4}M_{\odot}$ in the lensing zone, a program of worldwide 1m-class telescopes can expect several detections a year — even with 50% efficiency due to poor weather. Note that unlike radial velocities and astrometric techniques, microlensing has the potential to produce a detection of jovian mass object at jovian radii using photometric data that span only about 40 days, of which the anomaly itself may occupy only 1-2 days.

3.5 Terrestrial ($m = 10^{-5}$ to $10^{-6} M_{\odot}$ mass) Planets

The unambiguous detection of terrestrial mass planets will require an extremely ambitious program of rapid sampling with very high precision photometry of a very large number of microlensing events. If bright giant sources are chosen as a means to decrease exposure times, a strategy must be in place to break the finite source size degeneracies which lead to large uncertainties in planetary mass and orbital separation. At the same time photometric precision must be maintained below 1% in order to combat signal dilution due to the finite source. Breaking the degeneracy will require extremely dense sampling (several times an hour in the wings of the planetary event) in order to see higher order effects in the light curve, or simultaneous dense sampling in the optical and infrared in order to obtain 1-2% color measurements with sufficient spectral baseline to measure limb darkening in a transited source [13]. If, on the other hand, fainter (smaller) bulge sources are chosen to mitigate the finite source effects and simplify the interpretation of earth-mass signatures, the challenge will be obtaining 1% photometric precision on stars at $V \gtrsim 20$ in exceedingly dense fields while maintaining the high sampling rate required for smaller mass planets against smaller sources (see Table III). New software reduction

techniques may be required to obtain photometry as close to the photon noise limit as possible.

Since the detection probability is much smaller for earth-mass planets than for jupiters, many more events must be monitored before meaningful limits can be placed on their numbers. From Table III, we see that if one requires a 4% deviation for 2.4 hours or more against giant sources, the sensitivity is nearly zero, so that even with 100 monitored giant alerts, less than one earth-mass planet would *optimistically* be expected a year. This probability would grow only very slowly with hard-won increases in photometric accuracy. If turn-off stars could be monitored with enough precision to detect 4% deviations, however, the situation brightens slightly to allow ~ 2 detected earths per every 100 in the lensing zone. Although one could reasonably expect 75-150 turn-off alerts per year when OGLE II and EROS II are in full operation and MACHO begins to alert on all bulge quadrants, monitoring from one site only will reduce these numbers by about 2/3, again bringing optimistic numbers of earth-mass detections to 1 per year.

Recall, however, that the Bennett & Rhie sensitivities assume that only those light curves that are significantly deviant for a period of time equal to $2t_E/400 \approx 2.4$ hours or longer can be detected [14]. For good characterization of earth-mass planetary anomalies against turn-off stars, sampling of 20 minutes will be required (Table III). Since the detection sensitivities against turn-off stars are limited by sampling rates, not anomaly amplitude, if continuous sampling rates of 3 times an hour can be achieved, sensitivities will be increased compared to Bennett & Rhie estimates, perhaps by a factor of 2.

In sum, a program aimed at earth-mass detection against giant source will require substantially more giant alerts than likely to be available in the foreseeable future, and will probably require simultaneous IR photometry to resolve finite source degeneracies. A program designed to detect earths against turn-off sources could be feasible if very rapid and precise photometry in super-dense fields can be performed on 150 or more turn-off alerts per season. This is likely to require telescopes of larger than 1m aperture at sites with excellent seeing, and improved crowded-field reduction software.

4 Proposed Recommendations to ESO

The question to which we now turn is “How can ESO take a significant and perhaps leading role in the detection of extra-solar planets via microlensing by making special use of its current (1998-2000) observing resources or those being discussed for implementation in the more distant future. Since experiments specifically designed for jovian-mass planets are already underway [16], emphasis here will be placed on augmenting or extending existing microlensing searches for high-mass planets. The possibility for the largest single step forward lies in the detection of terrestrial mass planets, an area in which an aggressive ESO-based campaign could result in a breakthrough in the fledgling field of extra-solar planet research.

4.1 Intermediate term: 1998-2000

As detailed in §2.4 and §3, microlensing searches are already being conducted for jovian mass planets using a network of telescopes in the southern hemisphere. The resulting 24-hour coverage is necessary for the characterization of the 1 – 2 day anomalies expected for this mass of planet (Fig. 4). In particular, beginning in 1998, the new optical/IR simultaneously-imaging cameras now being built at Ohio State University (PI: Prof. Darren DePoy) for the PLANET collaboration coupled with guaranteed bulge season observing from four PLANET sites should allow at least 50 giants per season to be monitored. The cameras will afford shorter exposures for giant alerts and provide the sensitivity to chromaticity expected for events that resolve the source. Other teams are also considering beginning dedicated planet searches [8]. How can ESO resources be best used in the jovian search?

Primary Alerts: Microlensing monitoring programs rely on alerts from the survey teams. In the past these have been provided primarily by MACHO, but this is expected to change during 1997 with the inauguration of OGLE II and EROS II alert systems. EROS II, in particular, which operates from La Silla, is expected to provide the largest fraction of giant source alerts, due to their modified detection strategy based on bulge area rather than depth. Support of the EROS II effort or any other ESO detection experiment focusing on increasing the number of microlensing alerts on bright stars will thus aid monitoring programs focussed on the characterization of high-mass planets.

Target of Opportunity Spectroscopy: If the expected secondary (anomaly) real-time alert capability of the PLANET and GMAN teams is fully realized, flexible ESO scheduling and target of opportunity status on large apertures could allow spectra of the event to be taken throughout the short-lived anomaly; comparison baseline spectra could then follow at a later time. Such spectroscopy would provide detections or limits on the mass of the primary lens (ie, the parent star of the planet) by looking for evidence of a second stellar spectrum (at a different radial velocity) superposed on that of the source star. The relative contribution of the secondary spectrum would vary during and after the event, but achromaticity of the spectrum would be a strong indication of lensing as the source of the anomaly. (This spectral test for the first MACHO microlensing candidate was originally performed at ESO by Della Valle [18].) In addition, spectra would type the source star, thereby fixing (together with two-band photometry) its distance and physical radius. If the source is resolved, such spectra would then be invaluable in quantifying the geometry of the lensing through a quantification of the limb-darkening. Moreover, together with the detailed light curve from monitoring, such spectroscopy would provide a measure of the proper motion of the lens-source-observer system, yielding valuable, and otherwise unattainable information on lens kinematics. Some of these measurements may require 4m-class or larger telescopes in order to provide adequate S/N for dim lens stars against the bright giants and sub-giant sources important to existing jovian searches.

Due to the overwhelming dilution from finite source effects, earth-mass searches are probably best carried out against turn-off stars. Even so, the detection sensitivities, durations, and expected deviations are all expected to be quite small, requiring extremely rapid, precise monitoring of a very large number of (faint, crowded) lensed stars. Success is likely to require improvements not only in the initial detection rates for lensed turn-off

stars, but also advancements in crowded-field photometry. In order to compensate for the low detection probabilities of earth-mass planets, larger apertures will be needed to monitor a very large number of events with fast sampling. This combination of technical challenges may preclude a serious microlensing search for earth-mass planets before the year 2000. In the final section of this report, however, such an ESO-based search is sketched.

4.2 Long term: Beyond 2000

Public and scientific attention has been refocused on extra-solar planets by the recent discoveries of high-mass planets around ordinary stars by the radial velocities technique [19,20]. The feasibility of detection of earth-mass planets (ie, those most plausibly capable of supporting earth-like life) has therefore been pushed to fore. In this challenging new human endeavor, ESO may be well-poised to take special advantage of its unique capabilities after the year 2000 in order to take a leading role in the discovery and characterization of terrestrial-mass planets via microlensing.

An ambitious microlensing search program for earth-mass planets has already been suggested by Tytler [21], with further quantitative details supplied by Bennett and Rhie [14] and Peale [8]. Their particular suggestion centers on four 2m-class telescopes scattered in longitude in the southern and northern hemispheres, one serving as an alert instrument to increase the numbers of alerts, and the other three providing follow-up monitoring.

It is important to note, however, that the longitude distribution necessary for the full characterization of 1 – 2 day jovian microlensing anomalies is not required for 2 – 5 hour terrestrial anomalies against turn-off stars. Observations from a single site observatory like ESO are thus disadvantaged via a 2/3 reduction in the total detection frequency, but not in the characterization of detected events. Furthermore, since image quality is crucial to precise monitoring in crowded southern fields — a consideration that is all the more important for the search for low mass anomalies against faint turn-off stars — ESO will be *uniquely* advantaged with the best observational site in the world at Paranal. What follows is one suggestion for how that advantage might be built into a challenging, long-term search at ESO for earth-mass planets in the Milky Way.

4.3 A Specific Proposal for a Paranal “Other Earths” Survey

Can an independent program at Paranal provide sufficient numbers of turn-off alerts and have sufficient detection (and characterization) sensitivity to earth-mass planets? The answer based on rough but considered quantitative arguments using existing observational experience and theoretical modeling appears to be “yes.”

We begin by assuming that ~ 10 data points are required for characterization of earth-mass anomalies, thus requiring sampling times of about 20 minutes if turn-off stars are used as sources. This increased frequency of sampling would be expected to increase the detection sensitivity estimates in Table III by about a factor of 2, yielding detection sensitivities of $\approx 4\text{--}5\%$. (By binning, another factor of 2-3 could be gained, but only at the expense of anomaly resolution and characterization.) For a fixed number of turn-off alerts, single-site observations reduce this sensitivity to $\approx 1.5\%$. Generally, poor weather

would reduce this estimate still further, but should not be a concern at Paranal. Thus, if every lens contains an earth-mass planet in its lensing zone, about 130 turn-off alerts would need to be monitored with 1% precision in order to expect 2 earth-mass detections per season.

The considerations of §3.3 indicate that 150 turn-off alerts is at the upper end of what may be reasonably expected in the near future. Even if this number can be achieved or even surpassed, many of these alerts will be ill-suited to precision monitoring due to confusion with near neighbors. *It may be prudent, therefore, to consider an independent observing program at ESO that not only monitors turn-off stars, but also provides its own turn-off alerts.*

Since the vast majority of alerts are toward the Galactic bulge, monitoring must take place during the roughly 120 days of the bulge season. Typical event durations ($\hat{t} = 2t_E$) of about 40 days then imply that at least 50 suitable turn-off events must be simultaneously monitored with 20 minute sampling. If these 50 fields are independent, this would allow only 24 seconds per exposure (including overhead), which is clearly inadequate to reach the required 1% photometry on these crowded $V \approx 20$ stars even with a 4m aperture. The solution requires more monitoring telescopes or overlapping fields.

The Napoli 2.5m Telescope

The proposed Napoli 2.5m telescope to be placed on Paranal may be capable of solving both of these problems. If equipped with a state-of-the-art, ultra-large field of view, high-resolution imaging detector, the Napoli 2.5m could conduct a microlensing search for turn-off source events and *simultaneously* monitor them with the same exposures.

A $16K \times 16K$ detector with a 1 square degree field of view has 2.7×10^8 pixels, each about $0.22''$ on a side. If the seeing is good enough to take full advantage of the pixel size, one star is generally resolvable for every 20 pixels in crowded fields, yielding 1.34×10^7 monitored stars. (Total confusion is reached at one star per seeing disk. With median seeing of $0.65''$ at Paranal, this implies 2.9×10^7 stars in the 1 square degree field of view.) With current reduction techniques, at any limiting magnitude, only about 30% of these stars will have point spread functions that are well-behaved enough to make them suitable for very precise photometry. This yields 4×10^6 suitable photometric candidates, the vast majority of which are turn-off stars.

Current precision photometry indicates that a 5 minute exposure with a 1m telescope can produce 5% median photometry on “suitable” $V=20$ candidates [16]. Much of the scatter can be identified clearly with systematics related to crowding and scattered (moon)light; if these effects can be quantified and corrected for, or eliminated through better reduction techniques, the scatter could reasonably be expected to decrease by a factor of two for the fainter events. Thus, if systematics can be controlled one might expect the Napoli 2.5m to perform 1% photometry on its “suitable” turn-off sources with 5 minutes of integration, with the increased aperture just compensated for by the need for increased S/N . Since sampling every 20 minutes is required, only four fields can be examined, even with negligible overhead. If the 15-second readout time of the $8K \times 8K$ mosaic for the ESO 2.2m (with the new FIERA controller) can be maintained on a larger $16K \times 16K$ mosaic for the Napoli Telescope, these overhead constraints may be realizable.

But will enough alerts be generated in four pointings? The optical depth to microlensing, defined as the percentage of source stars being lensed at any given time above a threshold of $A = 1.34$ (ie, $u \leq 1$) has been estimated to be $(3 - 4) \times 10^{-6}$ toward the bulge of the Milky Way [22,23]. This would imply that 14 stars would have $A > 1.34$ at any time in a typical Napoli 2.5m field. Monitoring four fields would thus yield 56 suitable events, for a total of about 168 over the 120-day bulge season.

This may underestimate, however, the number of alerts and the sensitivity to earth-mass detection that would result. Since monitoring would now be simultaneous with discovery, the rising part of the light curve — which would normally be pre-alert — is now being monitored, giving the proposed Paranal search greater efficiency than that estimated by Bennett & Rhie [14]. At Paranal, the *full* light curve, from $A = 1$ to peak to $A = 1$ would be monitored; Bennett & Rhie assumed that monitoring was possible only from $A = 1.59$ ($u = 0.75$) to $A = 1.13$ ($u = 1.5$). Furthermore, microlensing events not considered by Bennett & Rhie — those with peak magnification less than 1.34 — will be found and simultaneously monitored with the proposed Napoli experiment. If the threshold amplitude is $A = 1.13$, for example, the number of microlensing events will increase by a factor of 1.5 compared to the typical $A = 1.34$ threshold. In principle, even smaller amplitude events could be discovered. One might reasonably expect, therefore, that 250 microlensing events could be detected per season in such a program. The previously-estimated detection efficiency of 1.5% would then suggest that ~ 4 earth-mass planets could be detected per season if every lens had such a planet in its lensing zone. Lower amplitude events ($A < 1.34$) would increase the detectable range of projected orbital separation x for planets on both the high and low end, although the effect will be most pronounced for larger x .

The 1.8m Auxiliary Telescopes

The 1.8m Auxiliary Telescopes (AT) for the VLT could be used as an alternative or supplement to the Napoli 2.5m program proposed here. If equipped with similar very large format ($16K \times 16K$ detectors, two AT would have a combined performance similar to that of the Napoli 2.5m whenever they could be spared from other observing programs. Alternatively, if secondary alerts of on-going planetary anomalies could be made in real time (a formidable task at the required data rates), the AT could be used for rapid-follow up of single events without the need for ultra wide-field capability.

Expectations and Challenges

In sum, the combined advantages of a dedicated “detection + monitoring” planetary microlensing program at Paranal with a 1 square degree $16K \times 16K$ detector should result in ~ 4 terrestrial planet detections per bulge season, if all monitored lenses have an Earth-mass planet in their lensing zone. The total number of detected planets of all masses could easily be 10 times higher, depending on the relative frequency and distribution of terrestrial and jovian mass planets in the Galaxy. These estimates would imply that as many as 320 planets could be detected over an 8-year (bulge season only) period, somewhat higher than the Peale estimate of 200 ± 80 detections under the same assumptions of one detectable planet per lens [8]. The ability of the Paranal planet search to make statistical

statements about the frequency of planetary systems in the Galaxy, and the distribution in mass and orbital radii of those planets would be unparalleled. In the event that half of the lenses were binaries, and therefore perhaps less likely to have planetary systems (an uncertain conjecture), the numbers of detected planets would be halved, but the number of detected microlensing binaries would be greatly increased.

The Paranal approach differs from other suggestions in that it requires one 2.5m telescope at a single excellent site with a state-of-the-art detector, rather than four 2m-class telescopes scattered in longitude. Some multi-site coordination may be required for the full characterization of the larger-mass (longer duration) planetary anomalies, but the earth-mass survey would be independent. In addition, the Paranal survey would have enhanced ability to go beyond detection to the *characterization* of earth-mass anomalies. Furthermore, the 250 microlensing events such a survey would detect in the Galactic bulge per season, would be simultaneously monitored with the precision and frequency required to detect and characterize many other microlensing anomalies, resulting in a much deeper understanding of the nature of all Galactic lenses. Real-time anomaly detection would also allow the VLT to be used to obtain simultaneous spectra throughout the anomaly. Simultaneous imaging in more than one band, preferentially spanning the optical and near-infrared spectrum, would be highly beneficial for monitoring with either the AT or the Napoli 2.5m, as it would be sensitive to the chromaticity expected from source resolution by small mass planets and blending by light from the lens itself that would lead to a better characterization of the parent star as well as the planet. The observing program and reduction process should lend itself to automation so that eventually on-site personnel costs can be kept to a minimum.

In order to achieve the remarkable rewards of an ambitious extra-solar planet search will require meeting certain challenges:

- new data processing techniques must be devised to control the photometric systematics resulting from crowding and seeing,
- the enormous data flow ($16 \times$ current MACHO rates) must be quickly and efficiently managed, and
- real-time anomaly detection must be mastered so that all available time can be spent on the field with the anomaly throughout its (short) duration.

Should ESO decide to embark on such a program in the VLT era, the necessary preparatory steps in modeling, crowded-field data reduction and analysis should be taken in the intervening years (1998-2000).

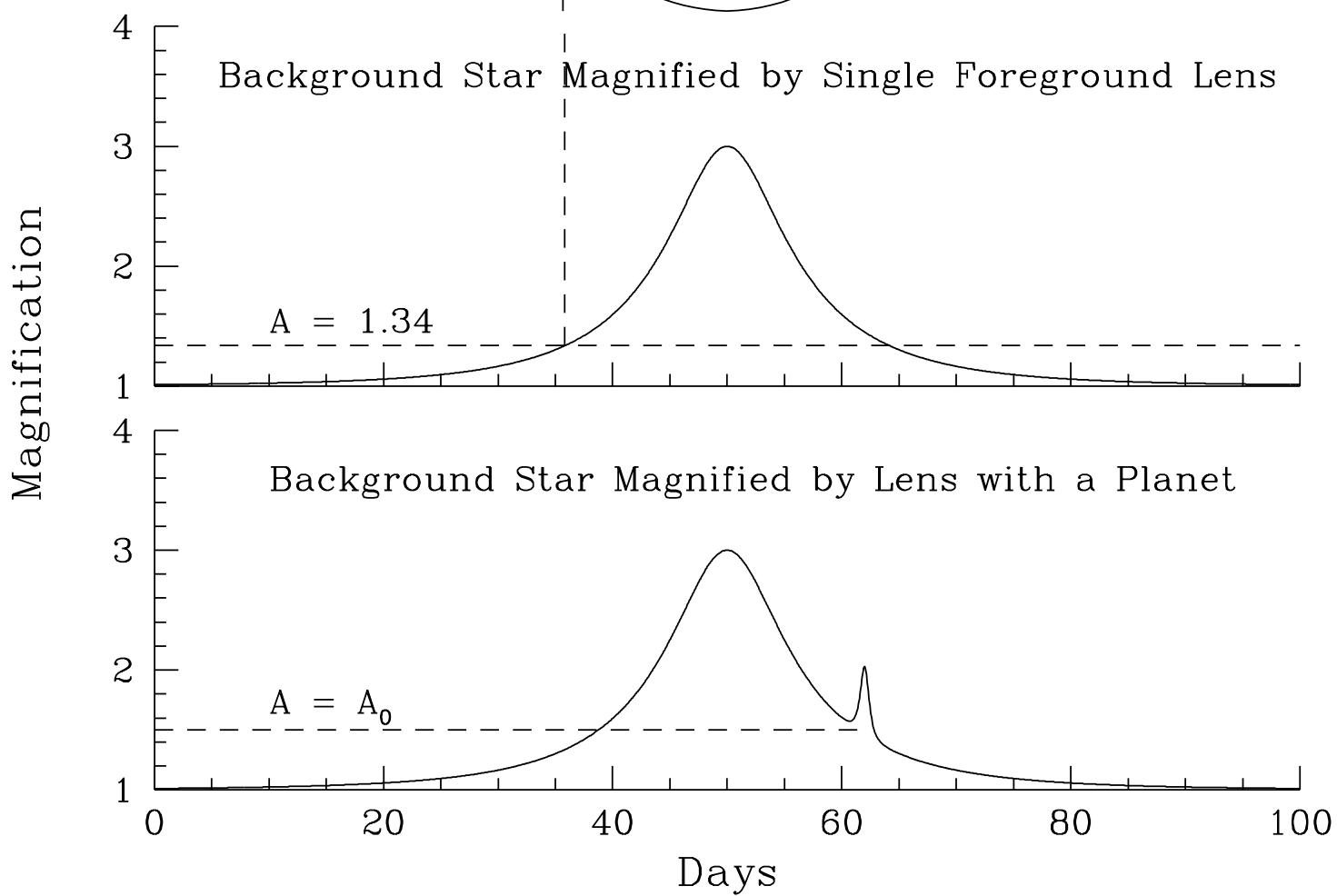
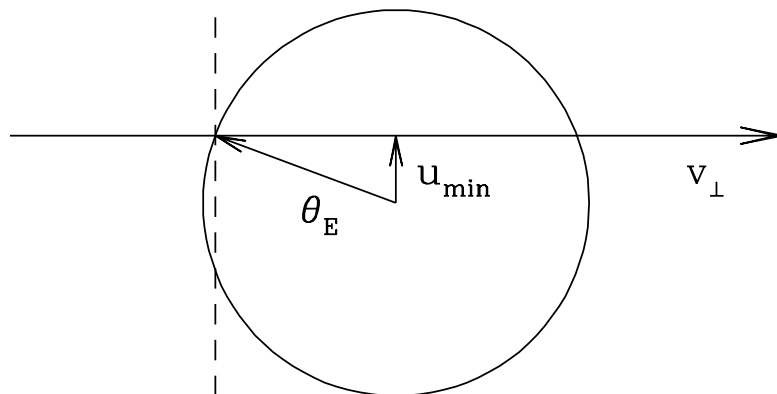
Finally, it must be stressed that the auxiliary rewards of an intense microlensing monitoring survey such as the one described here to the fields of microlensing, galactic structure and variable star research are so enormous as to be deserving of a separate document.

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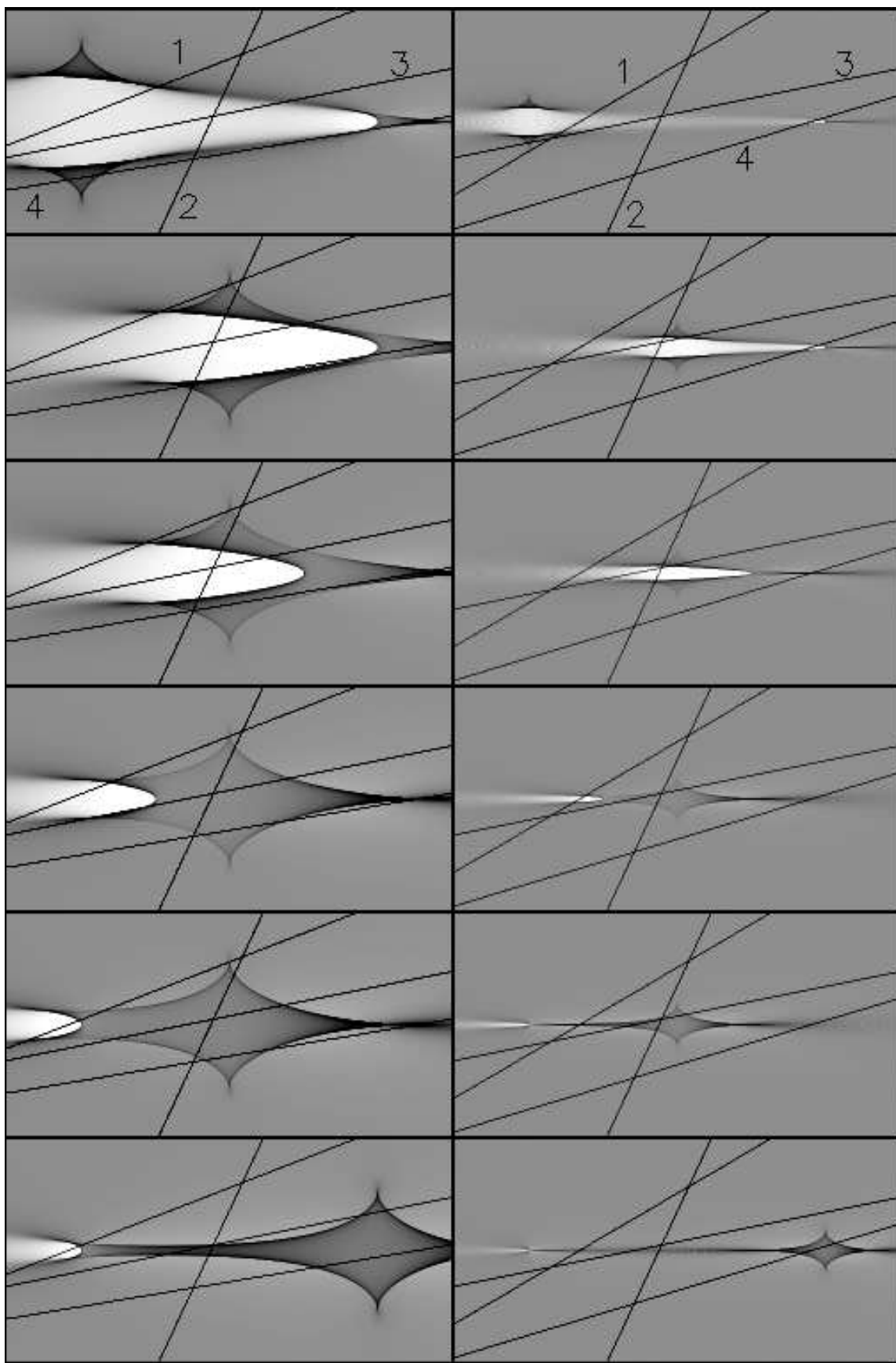
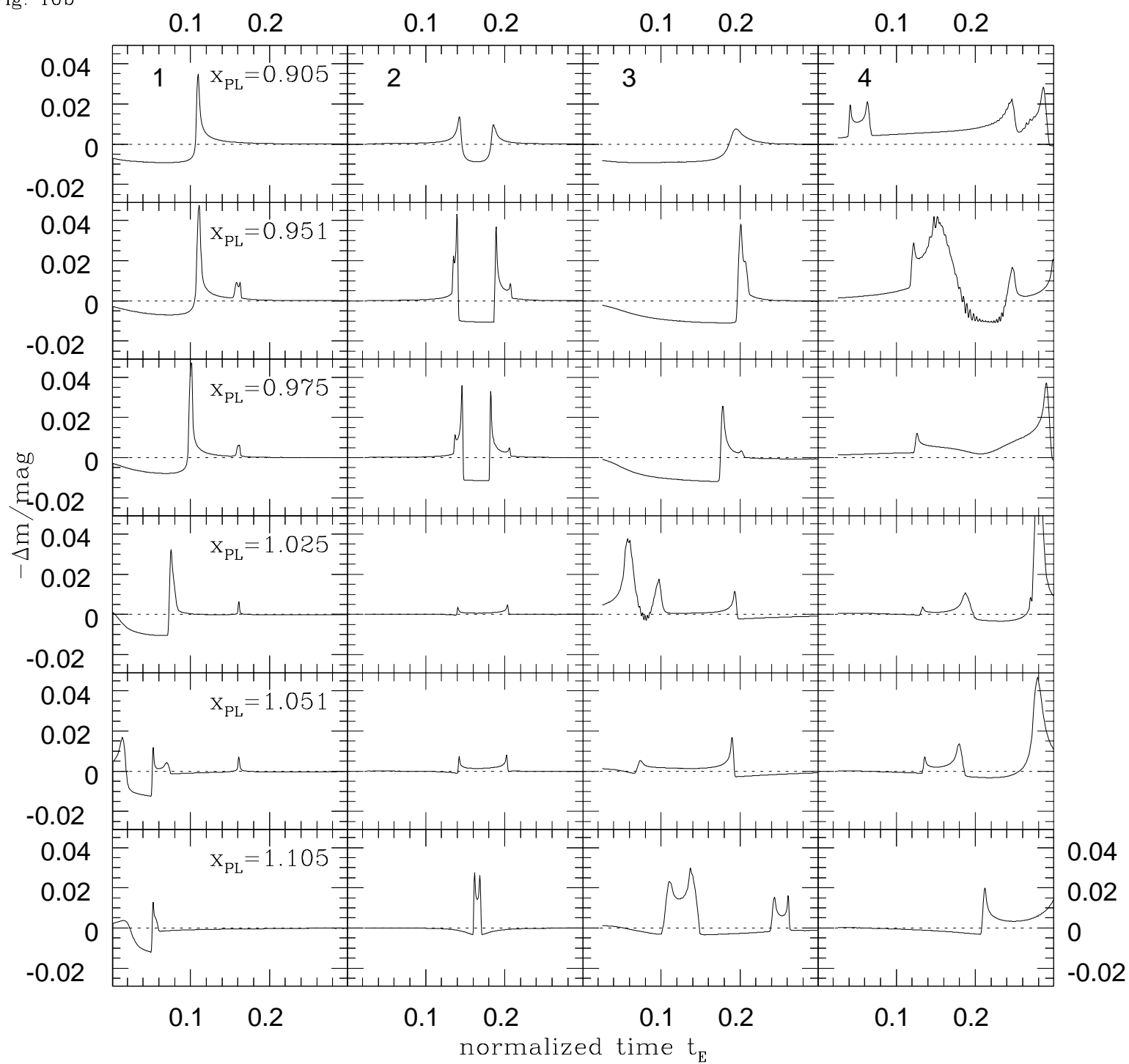
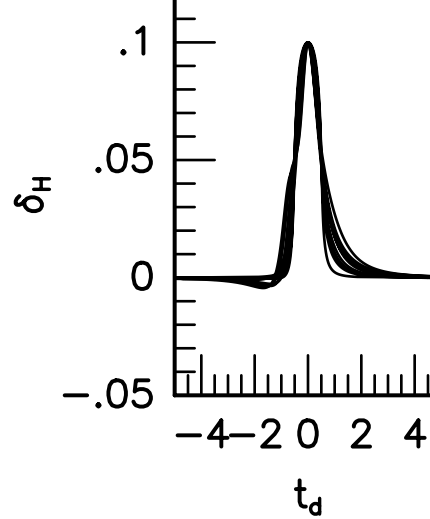
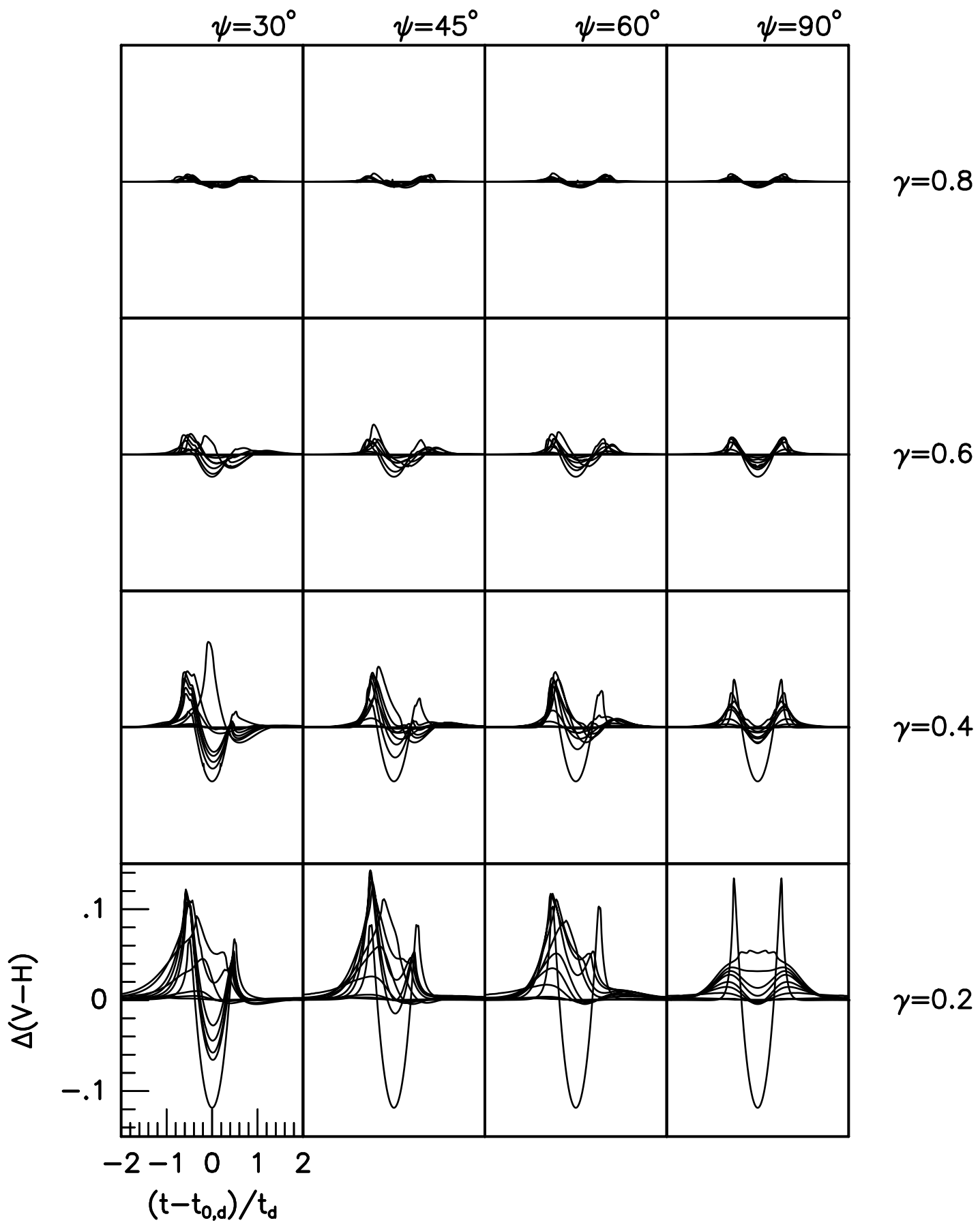


Fig. 10b



$\psi=30^\circ$ $\psi=45^\circ$ $\psi=60^\circ$ $\psi=90^\circ$ $\gamma=0.8$ $\gamma=0.6$ $\gamma=0.4$ $\gamma=0.2$ 



1995 PLANET Sampling (Sutherland & LaSilla stations)

